US009304150B2

(12) United States Patent
Johnson

(10) Patent No.: US 9,304,150 B2
(45) Date of Patent: Apr. 5, 2016

(54) **CLOSED CORE CURRENT PROBE**

(75) Inventor: **Kenneth W. Johnson**, Colorado Springs, CO (US)

(73) Assignee: **Keysight Technologies, Inc.**, Santa Rosa, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1103 days.

(21) Appl. No.: **13/249,836**

(22) Filed: **Sep. 30, 2011**

(65) **Prior Publication Data**

US 2013/0082695 A1 Apr. 4, 2013

(51) **Int. Cl.**

G01N 27/72 (2006.01)
G01R 15/20 (2006.01)
G01R 1/067 (2006.01)
G01R 15/18 (2006.01)

(52) **U.S. Cl.**

CPC ***G01R 15/207*** (2013.01); *G01R 1/06766* (2013.01); *G01R 1/06788* (2013.01); *G01R 15/183* (2013.01); *G01R 15/202* (2013.01)

(58) **Field of Classification Search**

CPC .. G01R 15/183; G01R 15/202; G01R 15/207; G01R 1/06766; G01R 1/06788
USPC .... 324/207.2, 251, 117 H
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,887,421	A *	11/1932	Newman	200/2
5,642,041	A *	6/1997	Berkcan	324/127
5,717,326	A *	2/1998	Moriwaki	324/117 H
6,512,359	B1 *	1/2003	Tamai et al.	324/117 R
6,940,265	B2 *	9/2005	Hauenstein et al.	324/117 H
7,250,748	B2 *	7/2007	Hastings et al.	324/117 R
7,526,971	B2 *	5/2009	Mandziuk et al.	73/866.5
7,583,073	B2 *	9/2009	Kumar et al.	324/117 R
8,330,453	B2 *	12/2012	Hotz et al.	324/207.2
8,680,843	B2 *	3/2014	Ausserlechner	324/126
2004/0164533	A1 *	8/2004	Pettypiece, Jr.	280/735
2006/0082357	A1 *	4/2006	Tsukamoto	324/126
2006/0284613	A1	12/2006	Hastings et al.	
2007/0257662	A1 *	11/2007	Mende et al.	324/117 R
2010/0156394	A1	6/2010	Ausserlechner et al.	
2011/0031966	A1 *	2/2011	Park et al.	324/240
2011/0036172	A1 *	2/2011	Park et al.	73/668
2011/0109303	A1 *	5/2011	Zhitomirsky	324/207.15
2011/0144933	A1 *	6/2011	Hoelscher	702/64
2013/0082695	A1 *	4/2013	Johnson	324/243
2014/0009146	A1 *	1/2014	Blagojevic et al.	324/252

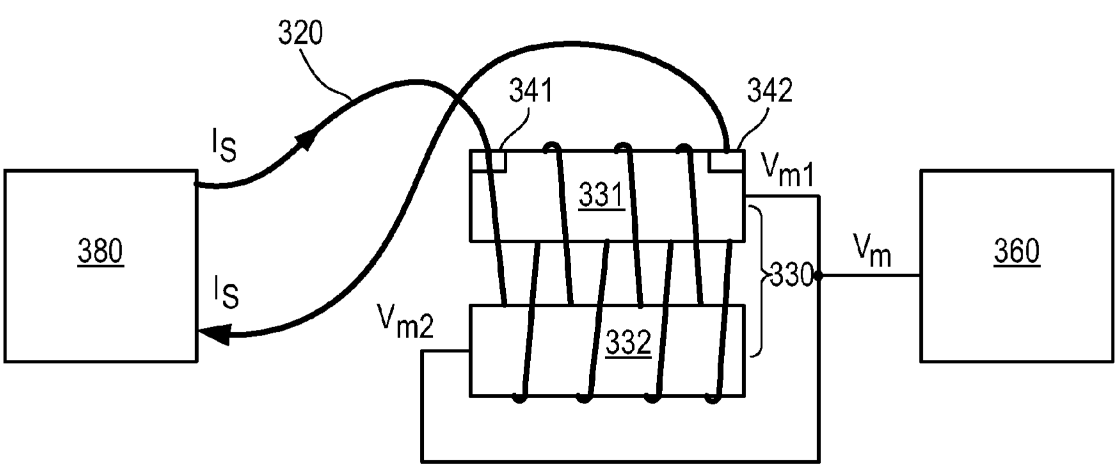
* cited by examiner

Primary Examiner — Jay Patidar

(57) **ABSTRACT**

A current probe enabling measurement of current of a signal in a circuit includes a ferrite core defining a gap, a wire wrapped around the ferrite core and a magnetic field sensor. The wire is configured to receive the signal from the circuit, where the current of the signal flowing in the wire generates a magnetic field in the ferrite core. The magnetic field sensor is positioned in the gap of the ferrite core, the magnetic field generated in the ferrite core flowing through the magnetic field sensor, which produces a voltage proportional to an intensity of the magnetic field. The current is measured based on the voltage produced by the magnetic field sensor.

16 Claims, 10 Drawing Sheets



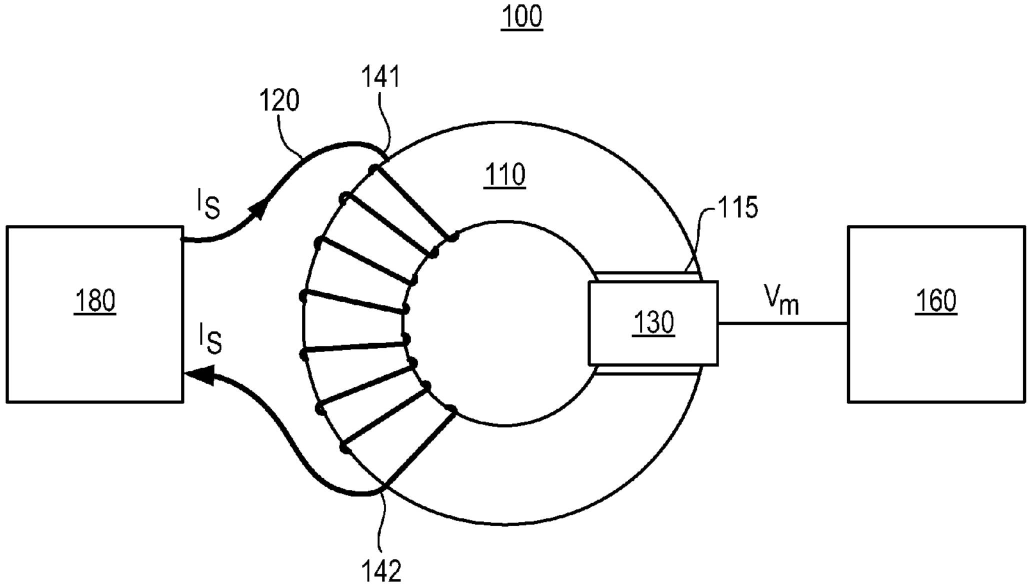


Fig. 1

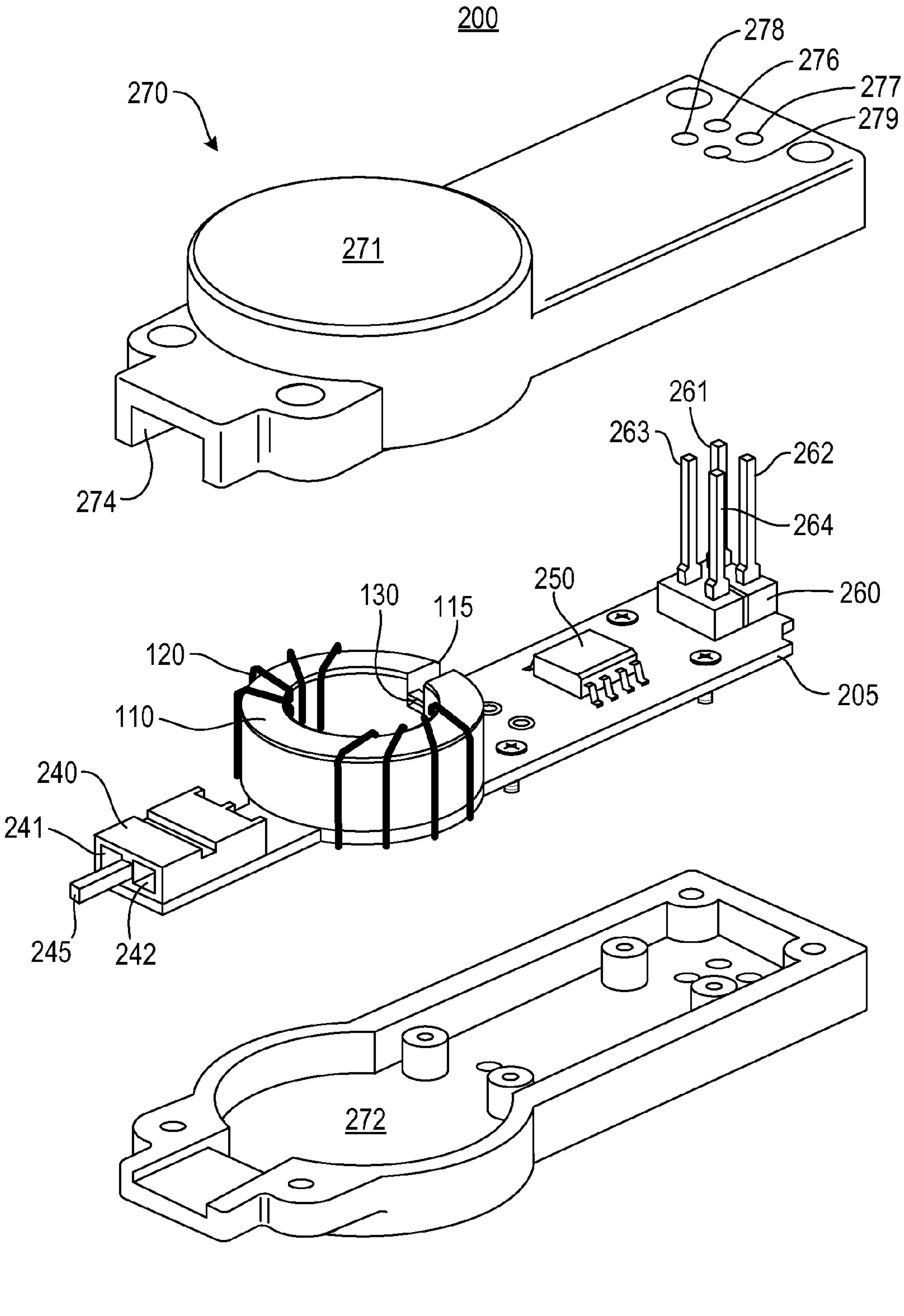

200
270
271
278
276
277
279
274
261
263
262
264
250
260
130
115
120
205
110
240
241
245
242
272

Fig. 2

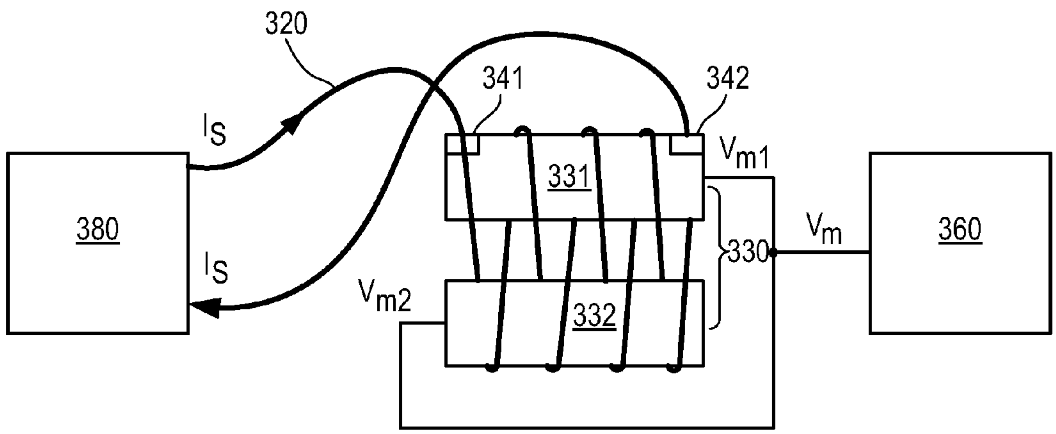


Fig. 3

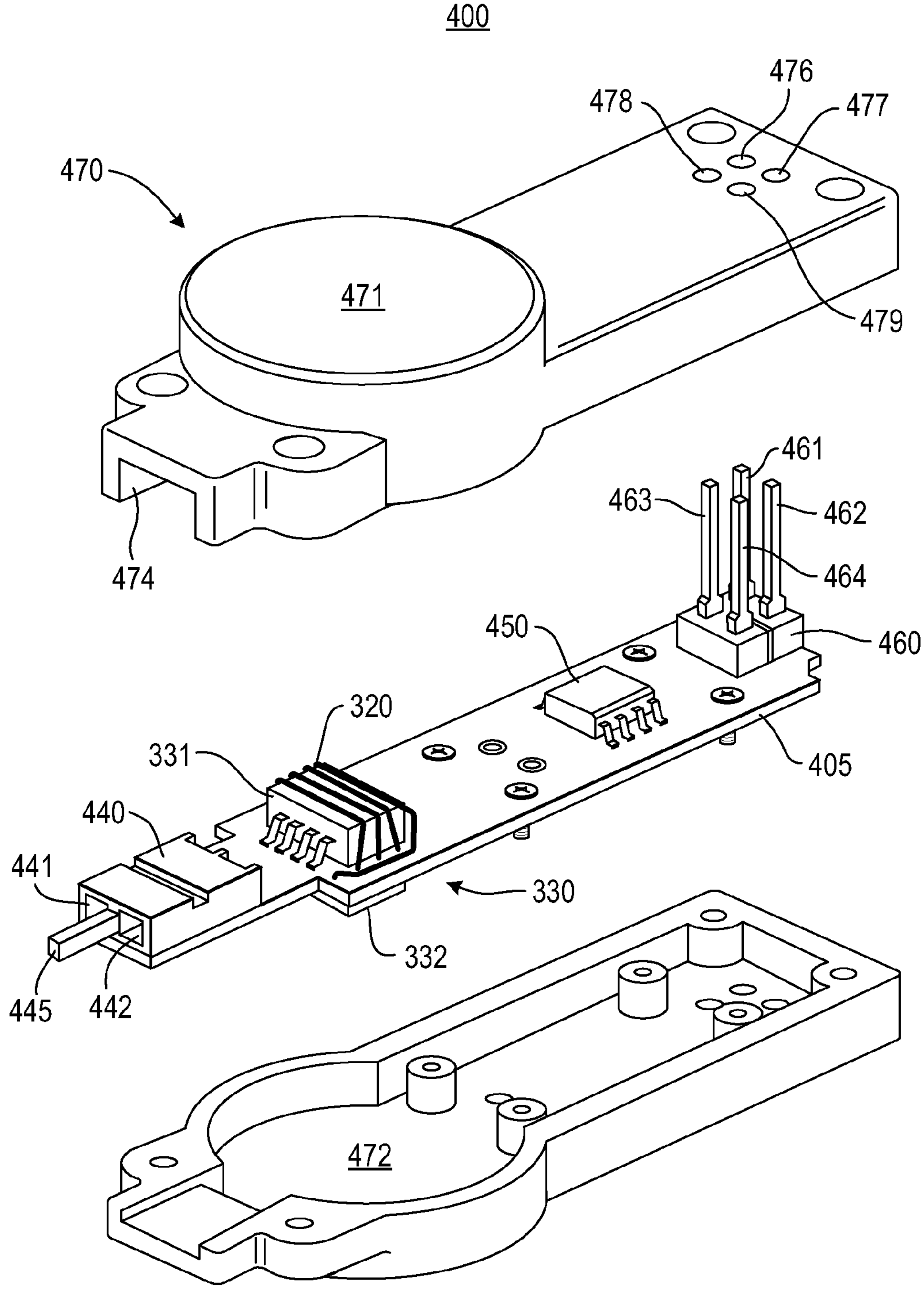

400
470
471
474
476
477
478
479
461
462
463
464
460
450
405
320
331
440
441
445
442
330
332
472

Fig. 4

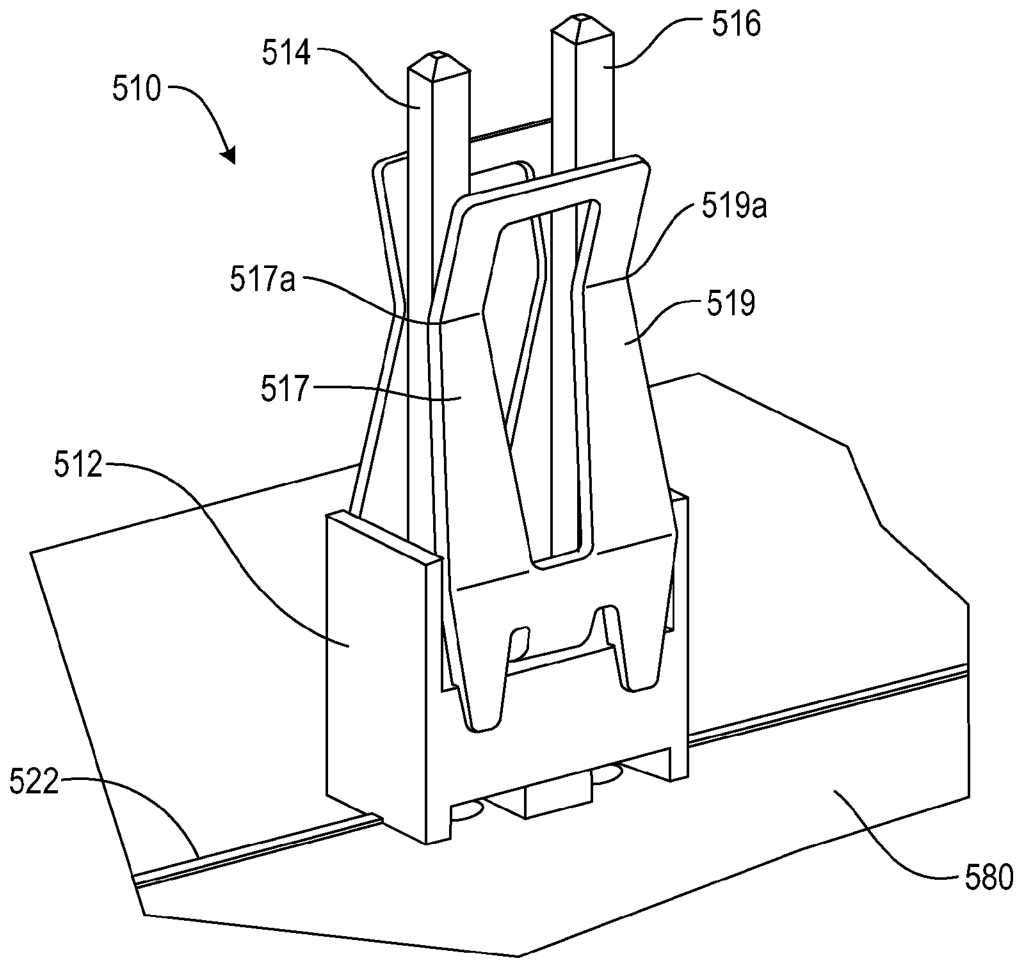


Fig. 5A

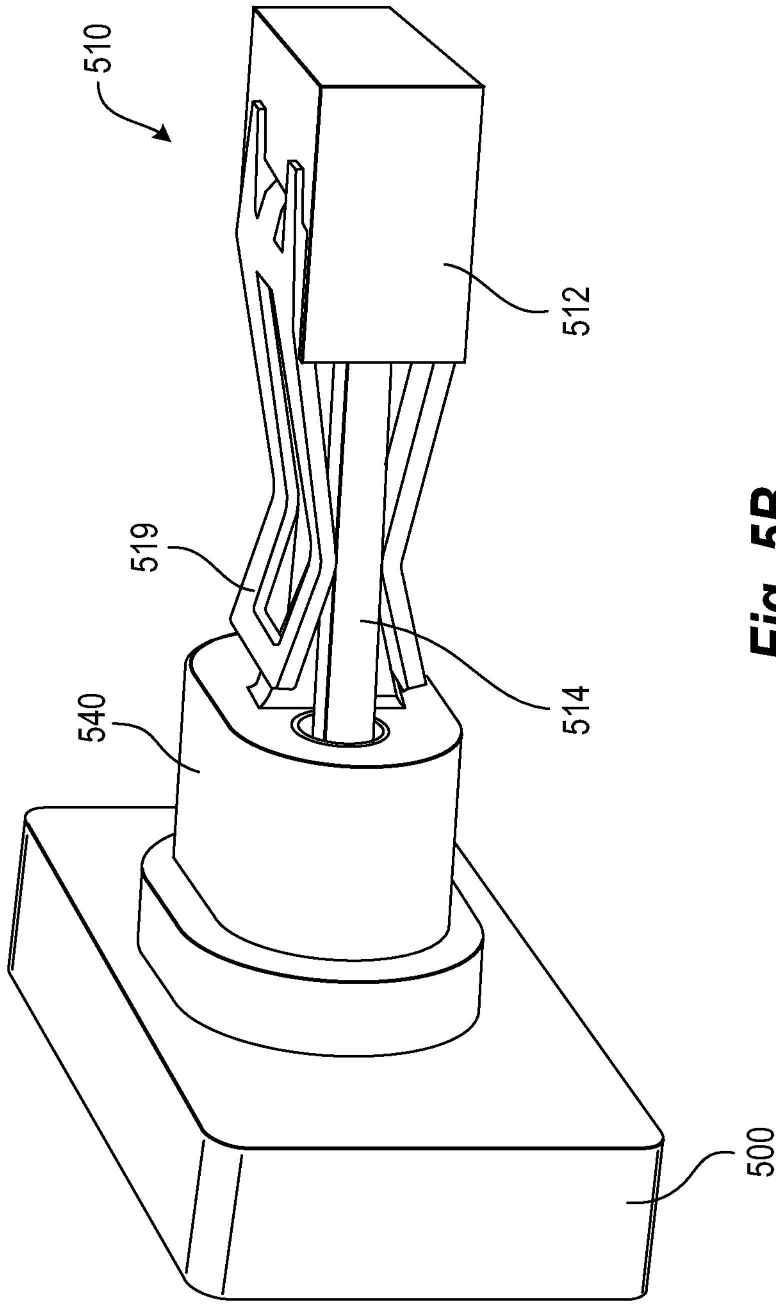


Fig. 5B

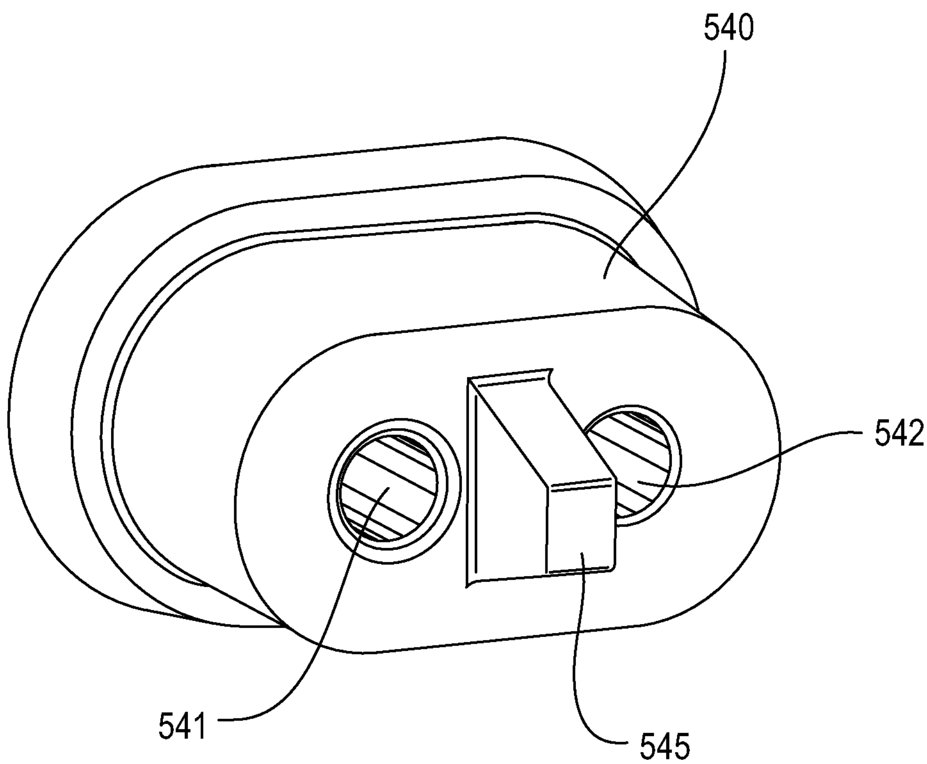


Fig. 5C

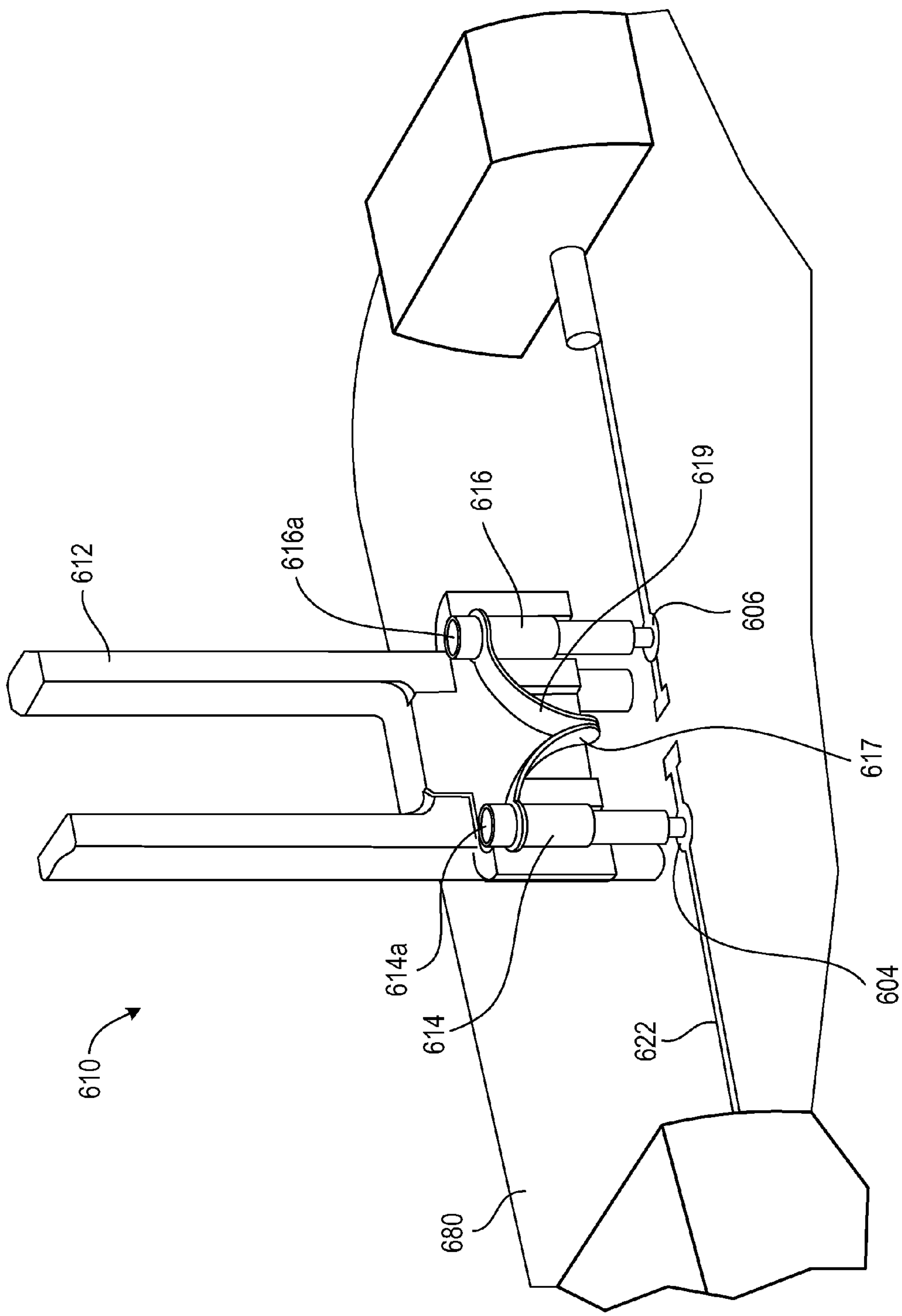


Fig. 6A

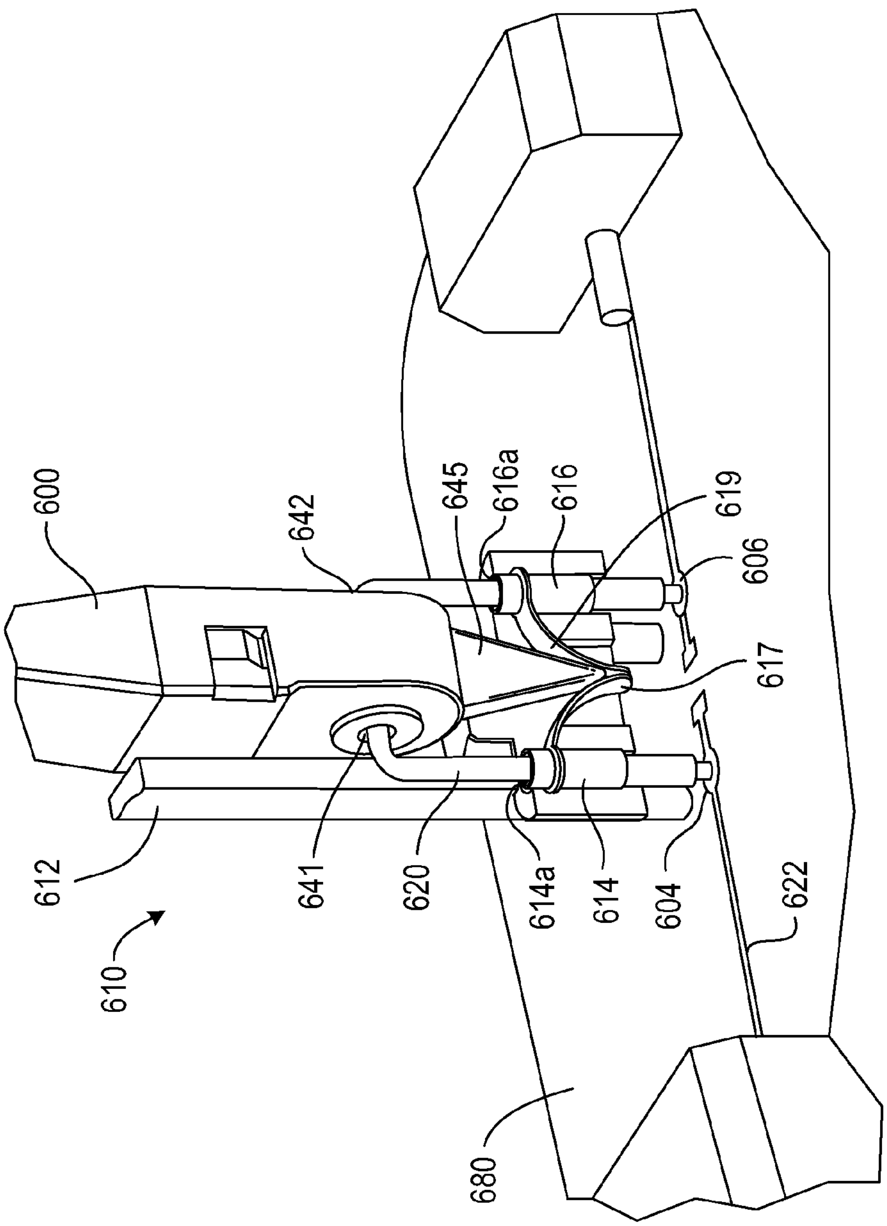

600
642
645
616a
616
619
606
617
612
641
620
614a
614
604
622
610
680

Fig. 6B

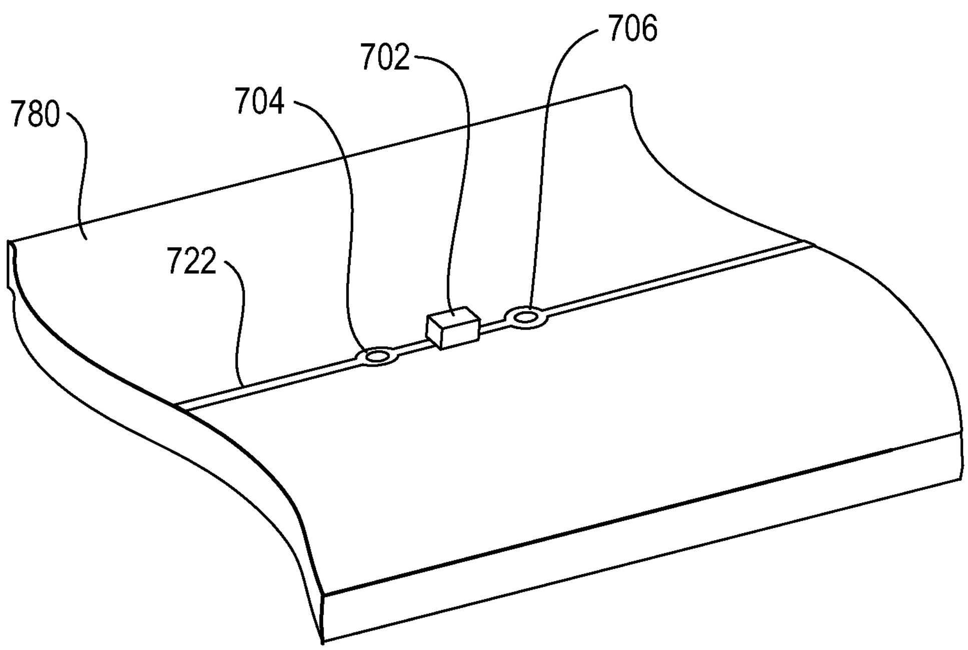


Fig. 7

CLOSED CORE CURRENT PROBE

BACKGROUND

Electronic test equipment, such as oscilloscopes, depends on probes to receive input signals to be analyzed. Conventional AC/DC current probes, in particular, utilize split core configuration. A split core configuration is one in which a magnetic field sensor, such as a Hall Effect sensor, works in conjunction with a ferrite core which concentrates the flux field. The ferrite core is split into two parts, so that the ferrite core can be opened and closed, enabling insertion of a conductor carrying the current to be measured.

Although split core probes may be reliable, they tend to be physically large in order to achieve the opening and closing feature, and thus conventional split core probes are substantially limited to larger targets, currents, conductors, and the like. For example, because the current probes are disproportionately large compared to the device under test (DUT), they create a mechanical burden on the DUT itself. More particularly, conventional current probes incorporate a loop of wire that is connected to the DUT, through which the measured current passes. A split core type current probe has a movable jaw that opens and closes around the loop of wire. This movable jaw configuration adds additional bulk to the current probe, and also increases manufacturing costs. Additionally, the large current probes can be position sensitive, so that movement of the current probes causes variations in measurements. Measurement results are thus not repeatable or otherwise inconsistent with respect to one another. Additionally, since split core probes allow the user to control the size and orientation of the current path through the split core, they suffer some repeatability issues.

Some conventional current probes are fixed core type, which do not include the movable jaws, and which are smaller and less costly than the split core type current probes. However, such current probes require that the wire carrying the measured current be threaded through an opening of the current probe. Thus, the use model requires that the wire be unsoldered in order to relocate the current probe from point to point on the DUT, which in turn requires that power be removed from the circuit. For example, the steps for using a conventional, fixed core type current probe generally include turning off the power to the DUT, unsoldering the wire from the circuit, threading the wire through the current probe, soldering the wire to the circuit, and applying power to the DUT. Of course, these same steps must be repeated every time the current probe is moved to another location or removed from the circuit.

Use of any type of conventional current probes typically involves physically cutting a conductive trace, e.g., on a printed circuit board, of the DUT. A wire is then soldered to each end of the cut trace, and the current probe is used to measure current passing through the soldered wire. The properties and position of the soldered wire affect the accuracy and repeatability of the measurement. For example, the length, width, shape (e.g., coiled) and orientation of the soldered wire all factor into the measurement result. Therefore, if any of these variables change between measurements, the results will not be repeatable or otherwise consistent with respect to one another.

SUMMARY

In a representative embodiment, a current probe is provided enabling measurement of current of a signal in circuit, such as a device under test (DUT). The current probe includes a ferrite core defining a gap, a wire wrapped around the ferrite core and configured to receive the signal from the circuit, and a magnetic field sensor positioned in the gap of the ferrite core. The current of the signal flowing in the wire generates a magnetic field in the ferrite core. The magnetic field generated in the ferrite core flows through the magnetic field sensor, which produces a voltage proportional to an intensity of the magnetic field. The current is measured based on the voltage produced by the magnetic field sensor.

In another representative embodiment, a current probe enabling measurement of current of a signal in a circuit, such as a DUT, includes first and second magnetic field sensors, and a wire wrapped around the first and second magnetic field sensors. The first magnetic field sensor is configured to produce a first voltage proportional to an intensity of a first magnetic field, and the second magnetic field sensor, arranged in a differential pair configuration with the first magnetic field sensor, is configured to produce a second voltage proportional to an intensity of a second magnetic field. The wire is configured to receive the signal from the circuit, the current of the signal flowing in the wire generating the first and second magnetic fields. The current is measured based on the first and second voltages produced by the first and second magnetic field sensors.

In another representative embodiment, a closed core current probe enabling measurement of a signal in a DUT includes magnetic field generating means for generating a magnetic field in response to a current of the signal, voltage producing means for producing a voltage proportional to an intensity of the generated magnetic field, and connection means for detachably connecting with a retention module connected in series with a circuit of the DUT carrying the signal being measured. The current is measured based on the voltage produced by the voltage producing means. Also, the connection means includes a protrusion configured to separate flexible contacts of the retention module to redirect the signal to the magnetic field generating means when the connection means are connected with the retention module.

BRIEF DESCRIPTION OF THE DRAWINGS

The illustrative embodiments are best understood from the following detailed description when read with the accompanying drawing figures. It is emphasized that the various features are not necessarily drawn to scale. In fact, the dimensions may be arbitrarily increased or decreased for clarity of discussion. Wherever applicable and practical, like reference numerals refer to like elements.

FIG. **1** is a simplified block diagram of a current probe circuit, according to a representative embodiment.

FIG. **2** is an exploded perspective view of a current probe, according to a representative embodiment.

FIG. **3** is a simplified block diagram of a current probe circuit, according to a representative embodiment.

FIG. **4** is an exploded perspective view of a current probe, according to a representative embodiment.

FIG. **5**A is a side perspective view of a retention module, according to a representative embodiment.

FIG. **5**B is a side perspective view of the retention module of FIG. **5**A, with a current probe connected, according to a representative embodiment.

FIG. **5**C is a side perspective view of a current probe connector for use with the retention module of FIG. **5**A, according to a representative embodiment.

FIG. **6**A is a side perspective view of a retention module, according to a representative embodiment.

FIG. 6B is a side perspective view of the retention module of FIG. 6A, with a current probe connected, according to a representative embodiment.

FIG. 7 is a top perspective view of a circuit configured to receive a retention module, according to a representative embodiment.

DETAILED DESCRIPTION

In the following detailed description, for purposes of explanation and not limitation, illustrative embodiments disclosing specific details are set forth in order to provide a thorough understanding of embodiments according to the present teachings. However, it will be apparent to one having had the benefit of the present disclosure that other embodiments according to the present teachings that depart from the specific details disclosed herein remain within the scope of the appended claims. Moreover, descriptions of well-known devices and methods may be omitted so as not to obscure the description of the example embodiments. Such methods and devices are within the scope of the present teachings.

Generally, it is understood that the drawings and the various elements depicted therein are not drawn to scale. Further, relative terms, such as "above," "below," "top," "bottom," "upper," "lower," "left," "right," "vertical" and "horizontal," are used to describe the various elements' relationships to one another, as illustrated in the accompanying drawings. It is understood that these relative terms are intended to encompass different orientations of the device and/or elements in addition to the orientation depicted in the drawings. For example, if the device were inverted with respect to the view in the drawings, an element described as "above" another element, for example, would now be "below" that element. Likewise, if the device were rotated 90 degrees with respect to the view in the drawings, an element described as "vertical," for example, would now be "horizontal."

According to various embodiments, an AC/DC current probe has a closed core, enabling the current probe to be much smaller than conventional split core current probes. In addition, the length and orientation of the current carrying conductor of the current probe and a retention module to which the current probe is detachably connected are fixed, so the current probe has greater sensitivity and measurement repeatability.

FIG. **1** is a simplified block diagram of a current probe, according to a representative embodiment.

Referring to FIG. **1**, current probe **100** enables measurement of current I_s from a signal passing through an electrical circuit, such as representative device under test (DUT) **180**. The current probe **100** is an AC/DC closed core current probe, and thus is much smaller than conventional split core current probes, as discussed above. The current probe **100** includes ferrite core **110**, which defines gap **115**. The ferrite core **110** may be formed of a high permeablility material, such as nickel-zinc compounds, for example, and is substantially circular in shape. Of course, the ferrite core **110** may be formed of various alternative high permeability materials and may have various different shapes, without departing from the scope of the present teachings.

Wire **120** forms a wire loop wrapped around the ferrite core **110**, such that current I_s flows through the wire **120** and generates a magnetic field in the ferrite core **110**. In the depicted configuration, the wire **120** is wound around the ferrite core **110** eight times (eight turns), for example. The intensity (magnitude) of the magnetic field varies directly proportionally with the number of turns of the wire **120**, and thus more turns will result in a more intense or stronger magnetic field and fewer turns will result in a less intense or weaker magnetic field for the same level of current I_s. The current probe **100** is connected in series with a circuit in the DUT **180**, as discussed below with reference to FIG. **7**, to measure the electrical signal passing through the DUT circuit, such that the wire **120** receives the current I_s from the DUT **180** at input port **141** and outputs the current I_s back to the DUT **180** from output port **142**. Generally, the intensity of the magnetic field is directly proportional to the amount of current I_s in the wire **120**, the number of turns of wire **120**, the size of the ferrite core **110**, and the permeability of the material forming the ferrite core **110**. Increases in the intensity of the magnetic field translate to increases in gain and thus the sensitivity of the current probe **100**.

Magnetic field sensor **130** is positioned in the gap **115** of the ferrite core **110**. The magnetic field sensor **130** may be a Hall Effect sensor, for example, although any compatible type of magnetic field sensor may be incorporated without departing from the scope of the present teachings. The magnetic field generated in the ferrite core **110** flows through the magnetic field sensor **130**, which produces measurement voltage V_m proportional to the intensity of the magnetic field. More particularly, magnetic flux flows out of one side of the gap **115**, through the magnetic field sensor **130** and into the other side of the gap **115**, and the magnetic field sensor **130** produces the measurement voltage V_m proportional to the intensity and direction of the magnetic flux. The current I_s in the DUT **180** can then be determined, e.g., by processing circuit **160**, based on the voltage V_m output by the magnetic field sensor **130**.

For example, when the magnetic field sensor **130** is a Hall Effect sensor, it has a plate to which voltage is applied. As the magnetic field impinges on the plate, it forces positive charges to one side of the plate and negative charges to the other side of the plate. This creates a voltage difference across the plate that is proportional to the strength of the field, and thus proportional to the amount of the current I_s flowing through the wire **120**. The current probe **100** (including the magnetic field sensor **130**) has a corresponding transfer function or conversion factor, expressed as Volts/Amp. For example, with a transfer function of 0.1V/A, the current probe **100** will output a voltage of 0.1 volts for every Amp of current I_s flowing through the wire **120**.

The intensity of the magnetic field varies directly proportionally to the magnitude of the current I_s flowing in the wire **120**. Also, the direction of the magnetic field corresponds to the phase of the current I_s flowing in the wire **120**. For example, when the current I_s has a sinusoidal waveform, the direction of the magnetic field reverses each time the waveform changes from positive to negative and vice versa. The phase of the voltage V_m produced by the magnetic field sensor **130** is determined by the direction of the magnetic field, and the phase of the current I_s is based on the phase of the voltage V_m produced by the magnetic field sensor **130**. Thus, the relative phases of the voltage V_m correspond to the relative phases of the current I_s, reproducing the sinusoidal waveform of the current I_s.

FIG. **2** is an exploded perspective view of a current probe, e.g., including the current probe circuit discussed above with reference to FIG. **1**, according to a representative embodiment.

Referring to FIG. **2**, closed core current probe **200** includes probe printed circuit board (PCB) **205** contained within housing **270**, which includes top and bottom housing parts **271** and **272**. Connected to the PCB **205** are ferrite core **110**, wire **120** wound around the ferrite core **110**, and magnetic field sensor **130** disposed in gap **115** defined by the ferrite core **110**, as discussed above. The housing **270** may be formed of metal or other durable material to protect the various components mounted to the PCB **205**, e.g., from physical impact, moisture, temperature, external magnetic and electrical fields, and the like.

Connector **240** is attached to one end of the PCB **205** to enable connection in series with a circuit (e.g., DUT **180**). The connector **240** includes input port (socket) **241** for receiving current I_s from the DUT circuit and output port (socket) **242** for outputting the current I_s to the DUT circuit after measurement. The input port **241** is connected to a first end of the wire **120** and the output port is connected to an opposite second end of the wire **120**, so that the current I_s flows from the DUT **180** through the wire **120**. The connector **240** also includes a beak or protrusion **245** extending from between the input and output ports **241**, **242**. The protrusion **245** is configured to separate flexible clamp contacts of a retention module fastened to the DUT circuit when the current probe **200** is detachably mounted in the retention module, discussed below with reference to FIGS. **5A-5C** and **6A-6B**. The input port **241**, the output port **242** and the protrusion **245** are exposed through current signal opening **274** formed by the top and bottom housing parts **271** and **272** of the housing **270**. Of course, other types of connectors may be incorporated for supplying the current I_s from the DUT **180** to the current probe **200** without departing from the scope of the present teachings.

The PCB **205** also includes (optional) amplifier **250** and voltage connector **260**. The amplifier **250** is configured to increase gain of the voltage V_m output by the magnetic field sensor **130**. The amplifier **250** may be an operational amplifier, for example, although other types of amplifying circuits may be included. The voltage connector **260** includes output voltage contacts **261** and **262** for outputting the (amplified) voltage V_m, indicative of the current I_s measured by the current probe **200**. The output voltage contacts **261** and **262** may be voltage and ground reference, respectively, for example. The voltage connector **260** further includes input voltage contacts **263** and **264** for receiving input to the current probe **200**, which may be applied to the magnetic field sensor **130** and the amplifier **350**, for example. In the depicted illustrative configuration, the output and input voltage contacts **261-264** extend through corresponding voltage signal openings **276-279**, respectively, in the top housing part **271** of the housing **270**.

FIG. **3** is a simplified block diagram of a current probe, according to another representative embodiment.

Referring to FIG. **3**, current probe **300** enables measurement of current I_s from a signal passing through an electrical circuit, such as representative DUT **380**. The current probe **300** is an AC/DC closed core current probe, and thus is much smaller than conventional split core current probes, as discussed above. The current probe **300** includes magnetic field sensor pair **330**, including first magnetic field sensor **331** and second magnetic field sensor **332**, which are physically arranged in a differential configuration. Accordingly, the first and second magnetic field sensors **331** and **332** form a differential pair. Each of the first and second magnetic field sensors **331** and **332** may be a Hall Effect sensor, for example, although any compatible type of magnetic field sensor may be incorporated without departing from the scope of the present teachings.

Wire **320** forms a wire loop wrapped around each of the first and second magnetic field sensors **331** and **332** in the magnetic field sensor pair **330**. The current I_s flows through the wire **320** and generates a first magnetic field around the first magnetic field sensor **331** and generates a second magnetic field around the second magnetic field sensor **332**. This creates greater magnetic gain since the magnetic flux from the wire **320** impinges on each of the first and second magnetic field sensors **331** and **332** from four sides. In the depicted configuration, the wire **320** is wound around each of the first and second magnetic field sensors **331** and **332** four times (four turns) in a figure-eight pattern, for example, although the number of windings and/or the winding patterns may vary, without departing from the scope of the present teachings.

Notably, in the depicted configuration, the number of turns of the wire **320** is the same around each of the first and second magnetic field sensors **331** and **332**. Accordingly, the intensities of the respectively generated first and second magnetic fields will be substantially equal to one another. Because the first and second magnetic field sensors **331** and **332** are arranged in a differential configuration, the first and second voltages V_{m1} and V_{m2} generated in response to the first and second magnetic fields will be added together, thereby creating a magnetic-to-voltage gain about twice that created by either of the first or second magnetic field sensors **331** and **332** alone. That is, the magnetic-to-voltage gain of the current probe **300** is the sum of the respective magnetic-to-voltage gains of the first and second magnetic field sensors **331** and **332**.

Further, the differential configuration provides greater immunity to external magnetic fields, which can be difficult and bulky to shield against. More particularly, external magnetic fields generate opposite external magnetic field voltages in the first and second magnetic field sensors **331** and **332**, which tend to cancel out, particularly where the first and second magnetic field sensors **331** and **332** have the same number of windings of the wire **320**, as in the present example. For example, the first magnetic field sensor **331** may generate a positive external magnetic field voltage in response to the external magnetic field, and the second magnetic field sensor **332** may generate a negative external magnetic field voltage in response to the external magnetic field, the negative external magnetic field voltage substantially canceling out the positive external magnetic field voltage, thereby removing effects of the external magnetic field on the current measurement.

The intensities (magnitudes) of the first and second magnetic fields of the first and second magnetic field sensors **331** and **332** vary directly proportionally with the respective number of turns of the wire **320**, and thus more turns will result in more intense or stronger magnetic fields and fewer turns will result in less intense or weaker magnetic fields for the same level of current I_s. The intensities of the first and second magnetic fields are also directly proportional to the amount of current I_s in the wire **320**. Increases in the intensities of the first and second magnetic fields translate to increases in gain and thus the sensitivity of the current probe **300**. The current probe **300** is connected in series with a circuit in the DUT **380**, as discussed below with reference to FIG. **7**, to measure the electrical signal passing through the DUT circuit, such that the wire **320** receives the current I_s from the DUT **380** at input port **341** and outputs the current I_s back to the DUT **380** from output port **342**.

The first and second magnetic fields generated by the current I_s in the wire **320** flows through the first and second magnetic field sensors **331** and **332**, respectively. In response, the first and second magnetic field sensors **331** and **332** produce first and second voltages V_{m1} and V_{m2} proportional to the intensities of the first and second magnetic fields, respectively. The first and second voltages V_{m1} and V_{m2} are combined (e.g., added) to provide combined measurement voltage V_m. The current I_s in the DUT **380** can then be determined, e.g., by processing circuit **360** based on the voltage V_m provided by the magnetic field sensor pair **330**. The first and second magnetic field sensors **331** and **332** thus combine to produce effectively twice the output voltage V_m than would be generated by either first and second magnetic field sensors **331** and **332** alone, thus providing the current probe **300** with greater sensitivity. When the first and second magnetic field sensors **331** and **332** are Hall Effect sensors, for example, they each have a plate to which voltage is applied. As the magnetic field impinges on each plate, it creates a voltage difference across the plate that is proportional to the strength of the field, and thus proportional to the amount of the current I_s flowing through the wire **320**, in accordance with a transfer function, as discussed above.

The intensities of the first and second magnetic fields vary directly proportionally to the magnitude of the current I_s flowing in the wire **320**. Also, the direction of each of the first and second magnetic fields corresponds to the phase of the current I_s flowing in the wire **320**. For example, when the current I_s has a sinusoidal waveform, the direction of the each of the first and second magnetic fields reverses each time the waveform changes from positive to negative and vice versa. The phases of the first and second voltages V_{m1} and V_{m2} are determined by the direction of the first and second magnetic fields, respectively. The phase of the current I_s is based on the phases of the voltages V_{m1} and V_{m2} produced by the magnetic field sensor pair **330**. Notably, the length of the wire **320** wrapped around the first and second magnetic field sensors **331** and **332** is substantially shorter than the wavelength of the current pulses passing through the wire **320**. Thus, there is not enough electrical length of the wire **320** for there to be negative effects that could be detected in the measurement.

FIG. **4** is an exploded perspective view of a current probe, e.g., including the current probe circuit discussed above with reference to FIG. **3**, according to a representative embodiment.

Referring to FIG. **4**, closed core current probe **400** includes probe PCB **405** contained within housing **470**, which includes top and bottom housing parts **471** and **472**. The housing **470** may be formed of metal or other durable material to protect the various components mounted to the probe PCB **405**, e.g., from physical impact, moisture, temperature, external magnetic and electrical fields, and the like. Connected to the probe Probe PCB **405** are first and second magnetic field sensors **331** and **332** in the magnetic field sensor pair **330** and wire **320** wound around the first and second magnetic field sensors **331** and **332** in an illustrative figure-eight configuration, as discussed above. The first and second magnetic field sensors **331** and **332** are physically arranged in a differential configuration, with the first magnetic field sensor **331** positioned on a top surface of the probe PCB **405** and the second magnetic field sensor **332** positioned on a bottom surface of the probe PCB **405** immediately beneath the first magnetic field sensor **331**. The figure-eight winding of the wire **320** must therefore pass through holes in the probe PCB **405**. Of course, alternative arrangements of the first and second magnetic field sensors **331** and **332** and/or alternative windings of the wire **320** may be incorporated without departing from the scope of the present teachings.

Connector **440** is attached to one end of the probe PCB **405** to enable connection in series with a circuit (e.g., DUT **380**). The connector **440** includes input port (socket) **441** for receiving current I_s from the DUT circuit and output port (socket) **442** for outputting the current I_s to the DUT circuit after measurement. The input port **441** is connected to a first end of the wire **320** and the output port is connected to an opposite second end of the wire **320**, so that the current I_s flows from the DUT **380** through the wire **320**. The connector **440** also includes a beak or protrusion **445** extending from between the input and output ports **441** and **442**, as discussed above with reference to the protrusion **245**. The input port **441**, the output port **442** and the protrusion **445** are exposed through current signal opening **474** formed by the top and bottom housing parts **471** and **472** of the housing **470**. Of course, other types of connectors may be incorporated for supplying the current I_s from the DUT **380** to the current probe **400** without departing from the scope of the present teachings.

The probe PCB **405** may also include amplifier **450** and voltage connector **460**. The amplifier **450** is configured to increase gain of the voltage V_m, which is the sum of the first and second voltages V_{m1} and V_{m2} output by the first and second magnetic field sensors **331** and **332**, respectively. The amplifier **450** may be an operational amplifier, for example, although other types of amplifying circuits may be included. The voltage connector **460** includes output voltage contacts **461** and **462** for outputting the (amplified) voltage V_m, indicative of the current I_s measured by the current probe **400**. The voltage connector **460** further includes input voltage contacts **463** and **464** for receiving input voltage applied to the current probe **400**, as discussed above. In the depicted illustrative configuration, the output and input voltage contacts **461-464** extend through corresponding voltage signal openings **476-479**, respectively, in the top housing part **471** of the housing **470**.

Notably, the current probes **100**, **200**, **300** and **400** described above have greater sensitivity, and measurements performed using the current probes **100-400** are more repeatable, as compared to conventional current probes. The length of the wires **120**, **320** is constant, and with respect to the current probes **100** and **200**, the permeability of the ferrite core **110** is constant. Also, there are no variables dependent upon the user's handling of the connections, or the positioning of the current probes **100-400**, etc., particularly since they are closed core and thus much smaller than conventional split core current probes. Thus, each time the current probes **100-400** are connected in series with the DUT circuit, the ensuing measurements will be consistent with other measurements from the same point.

As mentioned above, the closed core current probes, according to the various representative embodiments, may be detachably mounted in a retention module that is fastened (permanently or temporarily) to the DUT circuit carrying the current to be measured. Configurations of the retention modules may vary, although each configuration includes at least fixed lengths and shapes of conductors (e.g., wires) leading to and from the DUT circuit in order to eliminate variations in measurement that may otherwise result from different conductor lengths. Each configuration further includes fixed mounting means to hold the current probe securely in place at a fixed distance and orientation with respect to the DUT circuit in order to eliminate variations in measurement that may otherwise result from variations in positioning of the current probe during the measurement process. Of course, the closed current probes discussed herein may be attached to the DUT circuit for receiving a current by any of a variety of means, which may or may not include use of a retention module, without departing from the scope of the present teachings.

FIG. **5**A is a side perspective view of a retention module, according to a representative embodiment, and FIG. **5**B is a side perspective view of the retention module of FIG. **5**A, with a closed core current probe connected, according to a representative embodiment. FIG. **5**C is a perspective view of connector **540** which may be attached to current probe circuitry (e.g., on PCB **205**, **405**, discussed above) to enable mounting of the current probe.

Referring to FIGS. **5**A and **5**B, surface mounted retention module **510** is configured to fit securely on the surface of DUT **580** via contacts (not shown) at a desired measurement area over conductive trace **522**, and to hold a closed core current probe **500** (which may be one of representative current probes **100-400** discussed above) in place and to provide electrical contact with the current probe **500** via conductive prongs **514** and **516**. The conductive prongs **514** and **516** have fixed lengths and shapes to provide stable, consistent and repeatable measurement results from the measurement process. The current probe **500** and/or the surface mounted retention module **510** may be repeatedly removed from and re-attached to the DUT **580** between measurements, without removing power.

The surface mounted retention module **510** includes the conductive prongs **514** and **516**, which extend from retention module body **512**. First and second flexible clamp contacts **517** and **519** press against the conductive prongs **516** and **514** at respective angled portions **517***a* and **519***a*. As shown in FIG. **5**A, the first and second flexible clamp contacts **517** and **519** thereby create an electrical circuit or shunt between the conductive prongs **514** and **516** through which current from the conductive trace **522** passes whenever there is no current probe inserted into the surface mounted retention module **510**. The first and second flexible clamp contacts **517** and **519** are spring loaded so that they are generally forced toward one another, causing the first and second flexible clamp contacts **517** and **519** to exert pressure against opposite sides of the conductive prongs **514** and **516** at the angled portions **517***a* and **519***a* to create a solid mechanical and electrical connection.

Referring to FIGS. **5**B and **5**C, the connector **540** includes input port **541** and output port **442**, which are configured as discussed above with regard to input ports **241**, **441** and output ports **242**, **442**, respectively. The connector **540** further includes beak or protrusion **545**, having a partial wedge shape, for example, which extends from between the input and output ports **541** and **542**. The protrusion **545** is configured to force apart the first and second flexible clamp contacts **517** and **519** via mechanical contact with the angled portions **517***a* and **519***a* as current probe **500** is pressed into the surface mounted retention module **510**. The conductive prongs **514** and **516** are meanwhile insertable into the input and output ports **541** and **542**, respectively, making electrical contact with the current probe circuit of the current probe **500**. As the protrusion **545** forces apart the first and second flexible clamp contacts **517** and **519**, the angled portions **517***a* and **519***a* break physical and electrical contact with the conductive prongs **514** and **516**, eliminating the shunt and redirecting the current in the conductive trace **522** of the DUT **580** (e.g., current I_s) to flow through the current probe **500** via the input and output ports **542** and **542**, as discussed above. This enables measurement of the current by the current probe **500**. In an embodiment, the conductive prongs **514** and **516** make contact with the input and output ports **541** and **542** before the protrusion **545** opens the shunt, so that the flow of the current is not interrupted.

In various configurations, the retention module body **512** of the surface mounted retention module **510** may be formed of various lightweight materials capable of supporting the current probe **500**, such as plastic, and the conductive prongs **514** and **516** and the first and second flexible clamp contacts **517** and **519** may be formed of various conductive materials, such as copper or aluminum, for example. The protrusion **545** of the surface mounted retention module **510** may have a width compatible with circuits of a typical PCB, for example, in a range of about 0.1 inch to about 0.2 inch. The surface mounted retention module **510** may be configured for use with types of current probes other than those discussed herein.

FIG. **6**A is a side perspective view of a retention module, according to another representative embodiment, and FIG. **6**B is a side perspective view of the retention module of FIG. **6**A, with a closed core current probe connected, according to a representative embodiment.

Referring to FIGS. **6**A and **6**B, surface mounted retention module **610** is configured to fit securely on the surface of DUT **680** at a desired measurement area, and to hold a closed core current probe **600** (which may be one of representative current probes **100-400** discussed above) in place throughout the measurement process, establishing electrical contact through retention module connectors **614** and **616**. The retention module connectors **614** and **616** have fixed lengths and shapes to provide stable, consistent and repeatable measurement results from the measurement process. The current probe **600** and/or the surface mounted retention module **610** may be repeatedly removed from and re-attached to the DUT **680** between measurements, without removing power.

The surface mounted retention module **610** is shown mounted to the surface of the DUT **680** over conductive trace **622**. The surface mounted retention module **610** includes a probe receiving portion **612**, which is configured to enable slideable insertion and removal the current probe **600** (e.g., representative current probes **100-400** discussed above). The surface mounted retention module **610** also includes retention module connectors **614** and **616**, which may be mechanically fastened to the conductive trace **622**, as discussed below with reference to FIG. **7**. The retention module connectors **614** and **616** include sockets **614***a* and **616***a*, respectively.

In addition, the surface mounted retention module **610** includes a pair of flexible arch contacts **617** and **619**, respectively fastened to the retention module connectors **614** and **616**. As shown in FIG. **6**A, the flexible arch contacts **617** and **619** are touching one another, thus creating an electrical circuit or shunt between the retention module connectors **614** and **616** through which current from the conductive trace **622** passes whenever there is no current probe inserted into the surface mounted retention module **610**. The arched configuration generally causes the flexible arch contacts **617** and **619** to flex upward, resulting in the flexible arch contacts **617** and **619** exerting pressure on one another to create a solid mechanical and electrical connection.

FIG. **6**B, in particular, shows the current probe **600** inserted in the surface mounted retention module **610**. The current probe **600** includes input port **641**, output port **642** and protrusion **645**, substantially having a wedge shape, for example, which extends from between the input and output ports **641** and **642**. Notably, the current probe **600** in the depicted embodiment has a somewhat different style connector than the connectors **240**, **440** and **540**, discussed above. The input and output ports **641** and **642** are arranged on opposite sides of the housing as opposed to next to one another on one end of the housing. Also, instead of the retention module connectors **614** and **616** being inserted into the input and output ports **641** and **642**, the opposite ends of the wire **620**, which extends from the current probe **600** (via the input and output ports **641** an **642**) to enable insertion into the sockets **614***a* and **616***a* of the retention module connectors **614** and **616**, respectively. Otherwise, the circuitry of the current probe **600** is substantially the same as discussed above with reference to current probes **100-400**.

The protrusion **645** is configured to force apart the flexible arch contacts **617** and **619**, breaking the electrical and physical connections between them, eliminating the shunt and redirecting the current in the conductive trace **622** of the DUT **680** (e.g., current I_s) to flow through the current probe **600** via the input and output ports **641** and **642**, as discussed above. This enables measurement of the current by the current probe **500**. The probe receiving portion **612** holds the current probe **600** in a fixed position, and wire **620** is inserted into sockets **614***a* and **616***a* of the retention module connectors **614** and **616**, respectively, enabling measurement of the current via techniques discussed above with reference to FIGS. **1-4**, for example.

At a basic level, the surface mounted retention module **610** essentially functions as a traditional 0.1 inch connector, for example. The current probe **600** plugs into the surface mounted retention module **610** much like mating two connectors, although the flexible arch contacts **617** and **619** act like a shunt when the current probe **600** is not inserted, allowing the flow of current between the contacts **604** and **606**. As mentioned above, the current probe **600** includes the protrusion **645** (exaggerated for clarity) configured to open the connection between the flexible arch contacts **617** and **619** after the current probe **600** has made contact with the mating contacts in the surface mounted retention module **610**. This results in current flow from the conductive trace **622** being diverted from the shunt (closed flexible arch contacts **617** and **619**), and being rerouted through the wire **620** passing into the current probe **600**. Accordingly, the current flow through the DUT **680** is not interrupted, and the current probe **600** may be inserted and removed without removing power from the DUT **680**.

In various configurations, the surface mounted retention module **610** may be formed of various lightweight materials capable of supporting the current probe **600**, such as plastic, and the retention module connectors **614**, **616** and the flexible arch contacts **617**, **619** may be formed of various conductive materials, such as copper or aluminum, for example. The surface mounted retention module **610** may have a width compatible with circuits of a typical PCB, for example, in a range of about 0.1 inch to about 0.2 inch. The surface mounted retention module **610** may be configured for use with types of current probes other than those discussed herein.

As mentioned above, the closed core current probes of the various embodiments are connected in series with a DUT circuit carrying the current to be measured. FIG. **7** is a top perspective view of an illustrative circuit configured to receive a retention module, according to a representative embodiment, in which the current probe is detachably mounted.

Referring to FIG. **7**, the DUT circuit includes representative conductive trace **722**, which runs across the surface of representative DUT **780**. In order to accommodate current measurement, the conductive trace **722** may be physically cut in the area directly beneath a surface mounted retention modules, such as surface mounted retention module **510** discussed above with reference to FIGS. **5**A-**5**C and/or surface mounted retention module **610** discussed above with reference to FIGS. **6**A-**6**B. Alternatively, the DUT **780** and/or the conductive trace **722** may be designed with predetermined features enabling connection of the retention modules without having to manually cut the trace. For example, FIG. **7** shows the DUT **780** before attachment of a retention module, where the DUT **780** has a predetermined attachment region that includes removable zero ohm resistor **702** and holes in retention module contacts **704** and **706**.

To use the retention module, the resistor **702** is removed (e.g., by de-soldering), creating an open within the conductive trace **722** for performing current measurements. The retention module is then connected between the ends of the conductive trace **722** by inserting retention module connectors into the holes of retention module contacts **704** and **706**, respectively, and mechanically connecting them in place, e.g., by soldering. In alternative configurations, the retention module contacts **704** and **706** may include pads in place of the holes for soldering the connectors. Also, the holes may be through-holes that extend through a portion of the surface of the DUT **780** to an interior trace, enabling connection of the retention module. Of course, in the event the DUT **780** does not include a predetermined attachment region, the conductive trace **722** may be manually cut at the desired measurement location, and the retention module connecters may simply be soldered to the ends of the cut conductive trace **722**. In this case, the retention module connectors may be substantially L-shaped at the bottom to run along corresponding portions the conductive trace **722**, thus increasing the mechanical contact areas for improved soldering.

Generally, the retention modules (e.g., surface mounted retention modules **510**, **610**) are small surface mounted components that are attachable to a DUT. The surface mounted retention module serves as a mechanical locator and retainer for a closed core, AC or AC/DC current probe (e.g., current probes **100-600**), as well as a fixed path through which current travels when the current probe is not inserted. Use of the surface mounted retention module removes a number of user variables from the measurement process, including length of wire, position of probe, position of conductor relative to probe coil, magnetic field sensors and the like, resulting in more stable and repeatable measurements, and thus more sensitive measurements (greater sensitivity). Further, the current probe may be inserted, removed and/or relocated to another retention module without having to turn off power to the DUT or soldering/unsoldering a wire. It thus reduces the opportunity for error (e.g., bad solder joints, twisted wire, soldering to the wrong pad) and makes the installation, removal and movement of the current probe easier and faster.

While specific embodiments are disclosed herein, many variations are possible, which remain within the concept and scope of the present teachings. Such variations would become clear after inspection of the specification, drawings and claims herein. The invention therefore is not to be restricted except within the scope of the appended claims.

What is claimed is:

1. A current probe enabling measurement of current of a signal in a circuit, the current probe comprising:

a first magnetic field sensor configured to produce a first voltage proportional to an intensity of a first magnetic field;

a second magnetic field sensor arranged in a differential configuration with the first magnetic field sensor, and configured to produce a second voltage proportional to an intensity of a second magnetic field; and

a wire wrapped around and in physical contact with the first and second magnetic field sensors and configured to receive the signal from the circuit, the current of the signal flowing in the wire generating the first and second magnetic fields,

wherein the current is measured based on the first and second voltages produced by the first and second magnetic field sensors, and

wherein the wire is wrapped around the first and second magnetic field sensors in a figure-eight configuration.

2. The current probe of claim 1, wherein a magnetic-to-voltage gain of the current probe is a sum of magnetic-to-voltage gains of the first and second magnetic field sensors, respectively.

3. The current probe of claim 1, wherein the first magnetic field sensor generates a positive voltage in response to an external magnetic field, and the second magnetic field sensor generates a negative voltage in response to the external magnetic field, the negative voltage substantially canceling out the positive voltage, thereby removing effects of the external magnetic field on the current measurement.

4. The current probe of claim 1, wherein each of the first and second magnetic field sensors comprises a Hall Effect sensor.

5. The current probe of claim 1, further comprising:

a connector comprising an input port connected to a first end of the wire and an output port connected to a second end of the wire, wherein the connector is configured to be detachably mounted to a retention module connected in series with the circuit to be measured, the retention module comprising conductive prongs insertable in the input port and output port of the connector, respectively.

6. The current probe of claim 5, wherein the retention module further comprises first and second flexible clamp contacts configured to press against the conductive prongs when the current probe is not inserted, creating a shunt between the conductive prongs through which the signal from the circuit passes, and to break contact with the conductive prongs when the current probe is inserted, allowing the signal from the circuit to flow through the wire of the current probe; and

wherein the current probe further comprises:

a protrusion extending from the connector and configured to separate the first and second flexible clamp contacts from the conductive prongs of the retention module when the current probe is inserted.

7. A closed core current probe enabling measurement of a signal in a device under test (DUT), the closed core current probe comprising:

a printed circuit board;

magnetic field generating means for generating a magnetic field in response to a current of the signal;

voltage producing means for producing a voltage proportional to an intensity of the generated magnetic field, the voltage producing means comprising a pair of sensors arranged opposite one another on opposite sides of the printed circuit board, wherein the current is measured based on the voltage produced by the voltage producing means; and

connection means for detachably connecting the closed core current probe with a retention module connected in series with a circuit of the DUT carrying the signal being measured, the connection means comprising a protrusion configured to separate flexible contacts of the retention module to redirect the signal to the magnetic field generating means when the connection means are connected with the retention module,

wherein the magnetic field generating means comprise a wire wrapped around each of the sensors of the pair sensors and configured to receive the signal from the DUT.

8. The closed core current probe of claim 7, wherein the wire is wrapped around each of the sensors of the pair of sensors for multiple turns in a figure-eight configuration, the wire passing through the printed circuit board each turn to from the figure-eight configuration.

9. The closed core current probe of claim 7, wherein the pair of sensors comprises a differential pair of Hall Effect sensors, and the magnetic field generating means comprise a wire wrapped around each of the Hall Effect sensors of the differential pair of Hall Effect sensors and configured to receive the signal from the DUT.

10. A current probe enabling measurement of current of a signal in a circuit, the current probe comprising:

a first magnetic field sensor configured to produce a first voltage proportional to an intensity of a first magnetic field;

a second magnetic field sensor arranged in a differential configuration with the first magnetic field sensor, and configured to produce a second voltage proportional to an intensity of a second magnetic field; and

a wire wrapped around the first and second magnetic field sensors and configured to receive the signal from the circuit, the current of the signal flowing in the wire generating the first and second magnetic fields,

wherein the current is measured based on the first and second voltages produced by the first and second magnetic field sensors,

wherein the wire is wrapped around the first and second magnetic field sensors in a figure-eight configuration.

11. The current probe of claim 10, further comprising:

a printed circuit board, wherein the first magnetic field sensor and the second magnetic field sensor are arranged on opposite sides of the printed circuit board, and the wire wrapped around the first and second magnetic field sensors passes through the printed circuit board to form the figure-eight configuration.

12. The current probe of claim 10, wherein a magnetic-to-voltage gain of the current probe is a sum of magnetic-to-voltage gains of the first and second magnetic field sensors, respectively.

13. The current probe of claim 10, wherein the first magnetic field sensor generates a positive voltage in response to an external magnetic field, and the second magnetic field sensor generates a negative voltage in response to the external magnetic field, the negative voltage substantially canceling out the positive voltage, thereby removing effects of the external magnetic field on the current measurement.

14. The current probe of claim 10, wherein each of the first and second magnetic field sensors comprises a Hall Effect sensor.

15. The current probe of claim 10, further comprising:

a connector comprising an input port connected to a first end of the wire and an output port connected to a second end of the wire, wherein the connector is configured to be detachably mounted to a retention module connected in series with the circuit to be measured, the retention module comprising conductive prongs insertable in the input port and output port of the connector, respectively.

16. The current probe of claim 15, wherein the retention module further comprises first and second flexible clamp contacts configured to press against the conductive prongs when the current probe is not inserted, creating a shunt between the conductive prongs through which the signal from the circuit passes, and to break contact with the conductive prongs when the current probe is inserted, allowing the signal from the circuit to flow through the wire of the current probe; and

wherein the current probe further comprises:

a protrusion extending from the connector and configured to separate the first and second flexible clamp contacts from the conductive prongs of the retention module when the current probe is inserted.

* * * * *